A Cost Optimization of a Maintainable Solar Power Generator System

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***Abstract*—In this project, a solar power generator system was optimized for cost, furthered in design, built, and improved for use in a maintainable context. Through our work on characterizing the components of the solar power generator system, we were able to modify the existing setup to include a tesla turbine (rather than a back-driven cars AC scroll compressor) for the conversion of thermal energy into mechanical energy, as this component is more efficient in low-torque, high-RPM system. Finally, through our cost optimization of CSP systems much like this, we were able to determine that increasing the size of the system becomes less cost efficient as the money saved through a decrease in fuel consumed becomes less significant when compared to the cost of constructing and maintaining the system, over the course of a year.**

I. Introduction

A concentrated solar power generator system is a system in which a reflective parabolic trough focuses the light of the sun on some heat transfer fluid located in a dewar tube that runs the horizontal length of the trough. The heat transfer fluid is then boiled into steam and runs through a tesla turbine, which converts this thermal energy into mechanical energy through the rotation of a shaft. The rotational work of the tesla turbine is then used to drive a disk generator which converts this mechanical energy into electrical energy.

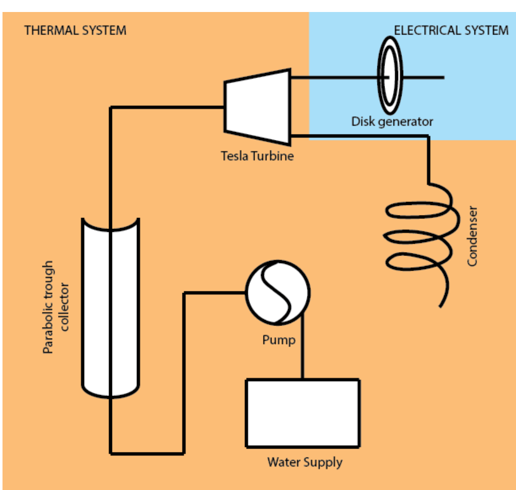

Fig. 1. The system block diagram of the solar power generator, including the trough, the tesla turbine, the disk generator, the condenser, the pump, and the water source

The work we did this semester on the solar power generator was a continuation of work done in earlier years, with the eventual goal of characterizing the system.. As the system had been sitting stagnant for many weeks, much of our initial work on it was to clean it, debug many of its issues, and improve the robustness of the system. Additionally, the system had previously been constructed for use with a scroll expander (which is a back-driven automobile scroll compressor), but as part of our improvement of the system, we configured it to work with an easily-machinable tesla turbine (better for use in high-RPM, low-torque applications). Through our work on the solar concentrator generator system, we ran it as an open loop system, as can be seen in Figure 1, for better debugging in the losses of the system.

In order to characterize the system, several sub-characterizations were made in the weeks leading up to the final experiment. We first tested the voltage output of a car scroll expander (a backdriven scroll compressor) under different input air pressures. Though this system is commonly used because of its extreme level maintainability, in a low-power system like the one we were working with often this scroll compressor is too high-torque to be useful for our tests. We then characterized the temperature difference of a dewar tube of our parabolic solar collector. Finally, we conducted an experiment on a tesla turbine (the same model as the one we were using in the final generator system), to determine its power output when it was connected in series to a disk generator via belt drive. All of these experiments were designed with the solar power generator in mind, as it was our ultimate goal to know approximately how much power the final system would output.

In addition to improving the system, we performed a cost-efficiency optimization on a parabolic solar collector generator similar to ours that has been discussed and detailed in prior works. This was done to address the viability of system setups for use in Sub-Saharan Africa.

II. Motivation

Having access to a reliable electrical energy source is crucial in regions without centralised power stations. The increased power supply has the potential of increasing the quality of life.

Besides increasing the quality of life, reliable power is also crucial in medical applications such as hospitals.

The use of a maintainable energy source empowers the local community. By implementing this CSP system in a community, the locals are given a possibility to sustain and maintain their own energy.

Using a renewable energy source (solar energy) provides us with a couple of major advantages. The often inefficient supply of non-renewable fuel is no longer needed and the emissions of greenhouse gases associated with our system

is dramatically lowered.

Using a Concentrating Solar system requires a relatively large area and a high DNI (Direct Normal Irradiation). The Ugandan Sub-Saharan conditions are therefore ideal for our CSP to operate in.

III. Background Information

A. CSP

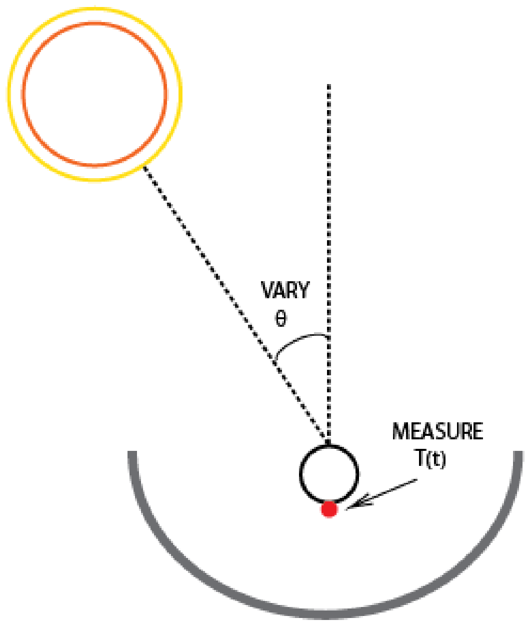

Fig. 2. Parabolic trough setup

Concentrated solar power technology harnesses natural solar energy to generate power. In solar collectors solar heat is used to heat a HTF (Heat Transfer Fluid), which then travels elsewhere to be converted from thermal energy into electrical or other types of power.To concentrate this solar energy, a reflective parabolic trough redirects incoming waves to hit and be absorbed by the central tube and fluid within. The tube of fluid in our parabolic trough is a dewar tube, which is quite normal for concentrated solar power devices. Dewar tubes are vacuum sealed and insulated to aid maintenance of the heated temperature of the fluid inside of them.

B. Tesla Turbine

A Tesla turbine is a flow turbine that uses drag forces instead of blades to generate high-RPM mechanical energy.

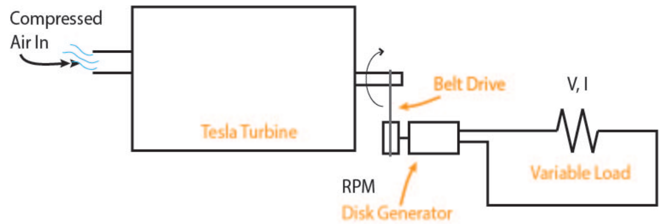

Fig. 3. Tesla turbine setup

In a Tesla turbine a high-pressured fluid enters a sealed chamber with closely packed parallel disks attached to a shaft. Because of the forced angle of entry, the fluid spirals onto the disks while pressing against them. Because of this drag force the disks start to spin, which in turn rotates the shaft. While the fluid drags onto the disk, the energy from the fluid is converted into mechanical rotational energy. As the fluid loses energy and speed, it spirals towards the center of the disks were the exhaust of the turbine is located. When in use in the CSP system, steam is forced through the Tesla turbine. The rotational work from the rotating shaft is used to drive a disk generator which converts the mechanical energy into electrical energy.

C. Disk Generator

The disk (or multi-coil) generator is a generator based on magnetic forces.

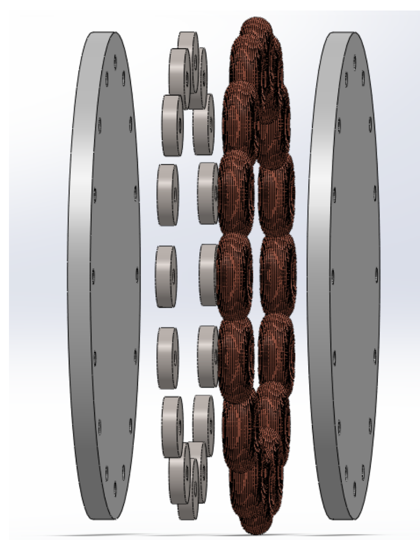

Fig. 4. Expanded diagram of the disk generator. The components from left to right are the magnet base plate, the magnets (alternating pole directions), the wire coils, and the coil baseplate.

The turning shaft of the generator is attached to a disk with a series of permanent magnets attached to its perimeter. The magnets are faced towards stationary coils consisting of conducting wires. When the shaft turns, the magnets move along the coils, therefore generating altering magnetic fields. These magnetic fields generate currents/electrical energy through the conducting wires.

D. Theoretical Rankine Cycle

The ideal operation of our CSP system follows a Rankine cycle, which is a thermodynamic cycle which is used to generate mechanical output from a heat input. In this case the heat input comes from the concentrated solar power, and the mechanical output comes from our tesla turbine, which is connected to the generator. The rankine cycle follows the following idealized steps: a pump pressurizes the fluid, moving it into the boiler, where heat coming in boils the fluid. The vapor phase fluid then expands through a turbine, producing work, and is condensed in a condenser before returning to the pump.

Ideally our system would run through this cycle at a steady-state level. However, we have not been able to achieve high enough rates of heat in with our current setup, and thus can only run the system as open loop for short periods of time. This is due partially to the fact that our collector trough is only 8 ft long (2.44 m) and our working fluid is water (due to safety concerns). The outlet of the condenser currently leads to a drain. Running the system briefly and not steady state can still give important information about the components of the system and the overall performance.

In the next version of the system, an organic, high molecular mass fluid with a low boiling point would be used. This would allow for heat recovery from lower temperature sources, such as sunlight, and would mean we could run our small test system closed-loop and steady state.

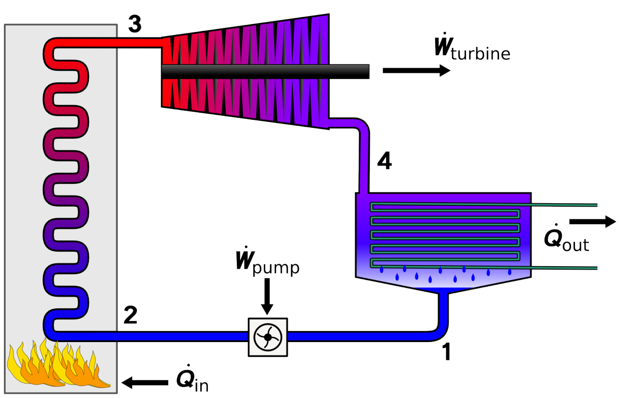

Fig. 5. Thermal rankine cycle system diagram

IV. Physical System

The system which we began our work with was built out of 80/20 aluminum framing and a curved reflector plate focused on a vacuum insulated tube. A lumber stand was made to support the tesla turbine and disk generator.

The tesla turbine we used was designed for teaching undergraduate engineering students how to properly machine mechanical components. Many communities in Uganda do not have access to CNC technology, so though the traditional fabrication technique uses CNC technology, we coordinated with the machine shop supervisor to come up with an alternative. The tesla turbine was redesigned to remove any necessity for CNC technology, and the current design is estimated to take 40 hours of machining to produce.

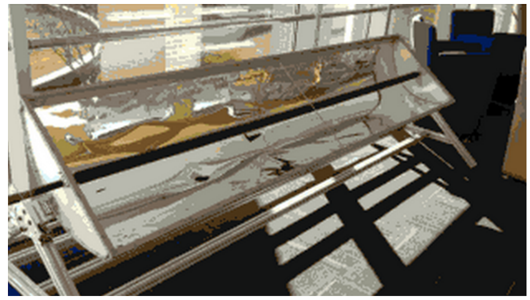

Fig. 6. The collector portion of our test rig (Monahan et al. 2013)

We made a number of additions to the test rig given to us, and we will outline them with motivations here. The previous system is described in Monahan et al., 2013.

The first change was to make a stand for the six 500W lamps that we use to simulate strong sunlight. This stand consisted of two u channel aluminum beams that ran the longitudinal length of the collector and were affixed to the two ends of the collector with sections of smaller u channel. The lights were then adhered to the surface of the stand. This stand allowed us to move or remove the lights easily, treating the lamp system as one object, not a collection.

When we switched from the automotive AC scroll compressor to the tesla turbine for use as a turbine, we had to change out the associated plumbing. When doing so, and routing the turbine above the waterline of the collector and not below as it had been before, we added in an accumulator (see Figure 7). The accumulator was built as a short length of tube coming down from a T on the piping coming out of the collector. This short length of tube had a valve on the end of it, which let us either drain the system or the accumulated water. The hope was that the water in the system would fall down into this accumulator.

In an attempt to keep the turbine from flooding with water, a stand was made to elevate the turbine above the water level of the trough. The stand was built from pine 2x4s and in plywood. Care was taken to enable access to the core components through holes in supporting panels.

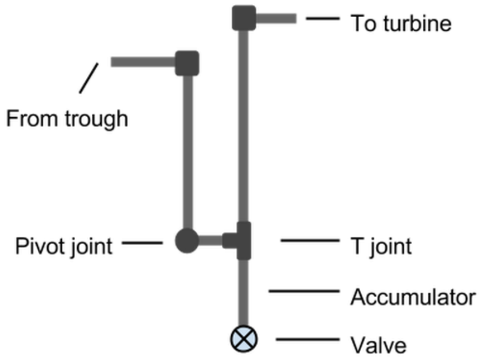

Fig. 7. Plumbing design of the accumulator

V. Data

VI. Cost-Efficiency Optimization

In order to determine the most viable system for sub-saharan Africa, we ran a cost optimization model for CSP systems similar to ours that have been discussed and detailed in prior works. This is quantified by determining the size of the system that can be paid off within a year such that after a years time, the starting cost of the system is less than or equal to the money saved comparing $/kWh of the solar collector to gasoline.

Using the system variables from Table 2, we designed an optimization function to determine the largest system possible system that will save enough money in the first year to cover the cost of the construction of the system. Since we are aiming to create a system to be built in low-economic areas, it is vital for the system to be financially viable.

We used the optimization function min[f(x)] = TotalCost(x) - ($/kWh of Diesel Fuel - $/kWh(x) of CSP) * time where x is the size of the system in m^2.

The total system cost is equal to a the cost of the solar panel per square meter and the cost of the power supply system which has to be upgraded based on wattage.

We used the system variables for a high temperature solar rankine cycle [1, MattThesis] to create a optimization model to determine the optimal system size.

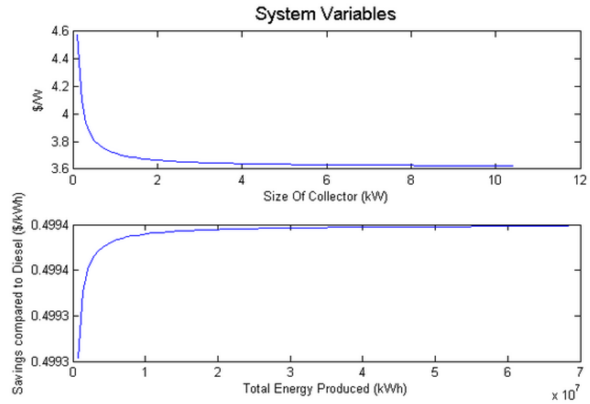

Fig. 8. The top figure demonstrates a learning curve trend as the system becomes cheaper per watt with increasing size. The bottom figure exhibits similar behavior, but is relative to the $0.50/kWh cost of diesel. The $/kWh of the CSP system asymptotically approaches $0.0065/kWh, meaning that increasing the size of the system becomes less cost efficient at larget scales.

VII. Future Work

In the future, we hope to do the same cost optimization for our model as we were able to for a more documented system. Building our collector and measuring its characteristics in Uganda would allow us to prove its viable.

We hope future groups will continue building the system where we left off. The biggest issue to solve is preventing the system from flooding by allowing only steam to pass through any parts after the trough in the system. This could include designing a more effective accumulator or ensuring that only steam comes out of the trough. We recommend that the entire test setup be tiled, such that the trough outlet is raised, to ensure that only steam is at the top at the outlet.

Another issue is that of the tesla turbine, which currently is not a sealed system. Water has been escaping via the shaft side of the turbine. This causes an issue as potentially corrosive water is getting into the bearing, flushing out the lubrication, and preventing a closed-loop, sealed system. We recommend finding a sealing solution, though leakage should be less in a purely steam environment.

VIII. Conclusion

In conclusion, we redesigned a CSP experimental test rig and optimized a theoretical CSP system. We found that it is crucial for a physical setup to achieve full steam output from the collector trough, as otherwise the system floods the turbine such that it will not turn. We developed a number of recommendations for ensuring full steam, most notably creating a tilted system such that the steam rises to the top of the trough tube on the side of the outlet. Finally, we performed a cost optimization of a similar CSP system and determined that increasing the size of the system becomes less cost efficient as the money saved through a decrease in fuel consumed becomes less significant when compared to the cost of constructing and maintaining the system, over the course of a year.

IX. Appendices

Appendix A
Optimization Model Assumptions

Optimization Variable, Units	Value
Beam Solar Insolation, W/m2	800
Efficiency	0.13
Cost of Trough, $/m^2	$220.00
Power Cost, $/W	$1.50
Labor Cost	$100.00
Time Run, years	1
Cost of Diesel, $/kWh	$0.50

Fig. 9. Variables in the optimization function

Appendix B
Model Code

```
kW = W./1000;

 CostPerArea = 220; %per m^2
 PowerBlockCost = 1.5*W;
 tCost = (Area.*220 + PowerBlockCost+100);

 figure(1);
 a=subplot(2,1,1);
 plot(kW,tCost./W);
 title(a,'System Variables','fontsize',14);
 xlabel('Size Of Collector (kW)');ylabel('$/W');
C1 = tCost./kW;

 time = 3600*5*365;
kWh = W./1000 * time;

% figure(2);
 subplot(2,1,2);
 plot(kWh,.5-tCost./kWh)
 xlabel('Total Energy Produced (kWh)');
 ylabel('Savings compared to Diesel ($/kWh)');
C2 = tCost./kWh;

% figure(2);
% subplot(2,1,2); plot(A,tCost);


% f = kW.*C1 - kW .* time .*C2;

 x0 = [1];
 [x,fval]=fmincon('objfun',x0,[],[]...
      ,[],[],[.5],[532],'constraint')

 f = tCost - (.5 - tCost./kWh).*time;
 figure(3);plot(Area,f)
 xlabel('Size of Solar Collector (m^2)');
 ylabel('Cost of CSP After 1 Year ($)');
 title('Optimization Behavior','fontsize',14)

%%%%%%% Objective Function %%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function f=objfun(x)
     Sbeam = 800; %W/m^2
     eff = 0.13;
     Qin = x*Sbeam;

    W = Qin * eff;
    kW = W./1000;

     CostPerArea = 220; %per m^2
    %Added the ceil because you can't upgrade your
    %   power system every fraction of a watt
     PowerBlockCost = 1.5*ceil(W/5)*5;
     tCost = (x.*220 + PowerBlockCost)

    C1 = tCost./kW;
     time = 3600*5*365;
    kWh = W./1000 * time;
     f =  tCost - (.5 - tCost/kWh)*time;

end

%%%%%%% Constraints %%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [c,ceq]=constraint(x)
         c = [];
%       c = (x(1) + x(2) - 1).^3;
%       c = x(1) + x(2) - 1
    ceq = [];
end
```

Appendix C
Experimental Designs

A. Scroll Expander

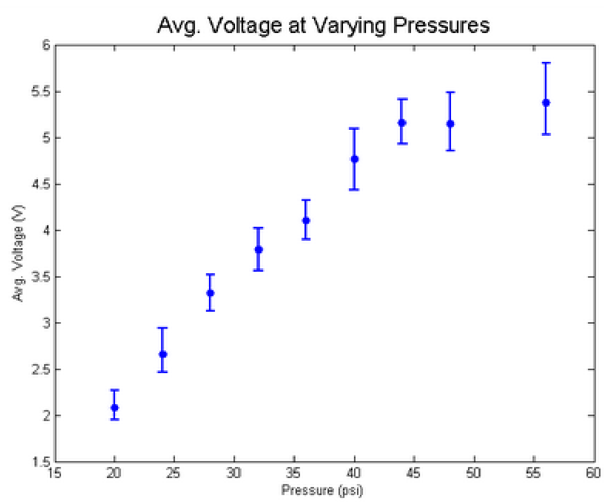

Fig. 10. The average voltage outputs of the DC motor as they relate to the input pressure of the scroll expander

Our data shows that at increasing input pressure to the scroll compressor, there is an increased voltage out produced by the connected DC motor. There is a trend shown in the above figure, that the average voltage increases with pressure with diminishing returns. If the voltage and power

are linearly correlated, this implies an optimal region of operations, and a point where increasing the pressure doesnt increase the power output of the system.

B. Tesla Turbine

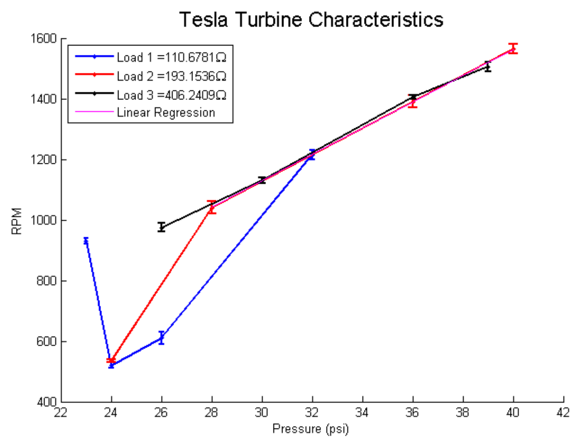

Fig. 11. Output rotational velocities compared to the air pressure inputs of the tesla turbine system.

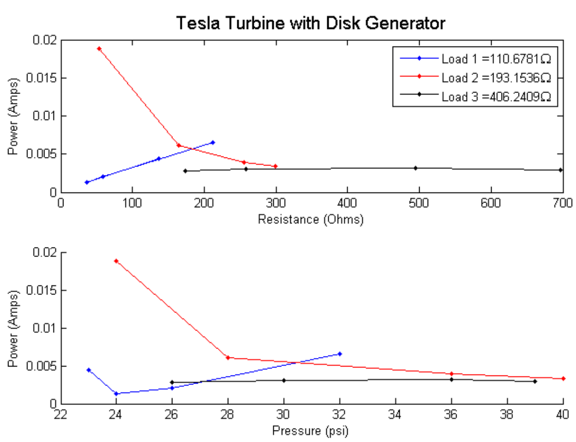

Fig. 12. Power against resistance for our system. Note the large variation in resistance values for one run of trials run with a constant load.

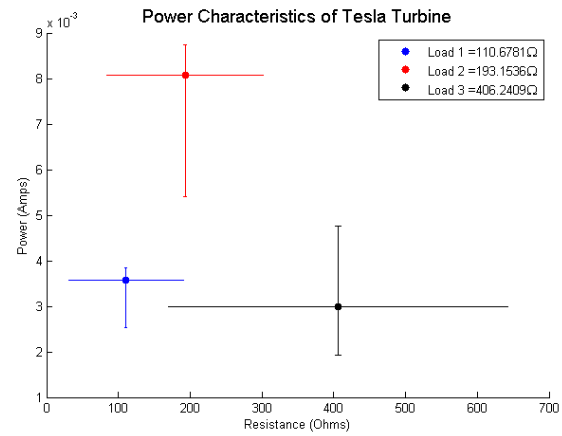

Fig. 13. The standard deviation is shown with the horizontal error bars. This is a result of the measured voltage and current ratio fluctuating during the trials. Despite this fact, there is an optimal region of resistance where we are getting a higher power out compared to both the larger and smaller loads. Even when the large standard deviation in the calculated resistance values is accounted for, a peak in the power output of 5500-8500 Amps at 100-300 Ohms is still indicated

A linear relationship between input air pressure and rpm of the Tesla turbine was observed during this experiment for pressures between 28 and 40 psi. The linear regime follows this equation:

$$RPM = 43.2506[psi^{-1}min^{-1}]*Pressure-167.6270[min^{-1}] \quad (1)$$

For input pressures with values lower than 28, the relationship between pressure and rpm became inconsistent. Around this ¡28 psi range we found we the system would not always start on its own, so we would have to start the spinning motion ourselves, at which point it was able to sustain itself. An outlier in the data was observed for an extremely low input pressure, which can be explained by the manual kick-start.

This evidence suggests that if there is a peak or plateau for the power vs pressure difference graph it is at a higher pressure than we investigated. This higher pressure range should be investigated in future work.

The calculated electric load values, obtained from the disk generator, had large error but still indicate the presence of a peak of 5500-8500 Amps at 100-300 Ohms in the power vs load curve.

C. Parabolic Trough

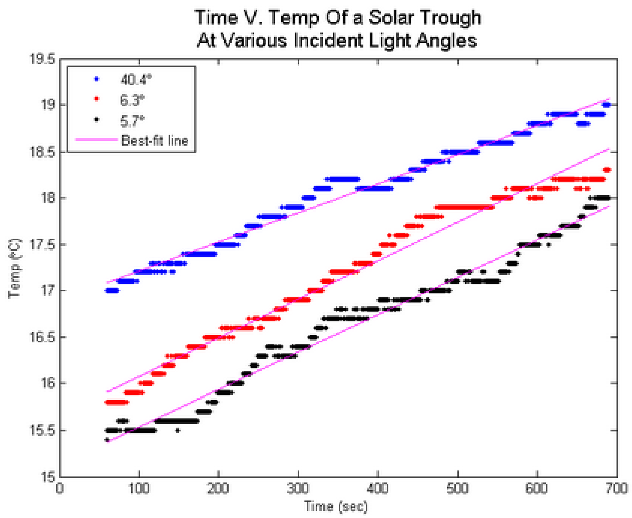

Fig. 14. Plot of the raw current and voltage readings from tests at different angles

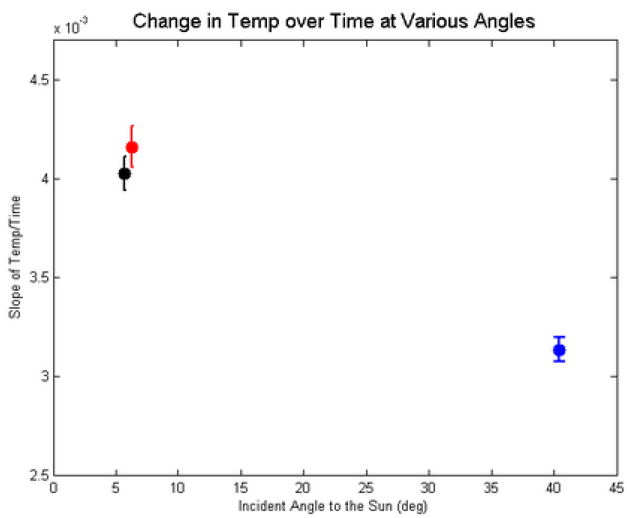

Fig. 15. Resistance and Power optimization curves at different angles

Our limited data seems to suggest a peak in the heating rate achieved above an incident light angle of 5.7 degrees and 40.4 degrees. The resulting slopes of our different trials were fairly similar, potentially within the bounds of error for the setup. There were many environmental inconsistencies as the tests were run outside in real sunlight, with no control for wind or ambient temperature and no mechanically precise rig to control the position of the light source. More trials are needed to determine a significantly accurate conclusions.

References

[1] H. Kopka and P. W. Daly, *A Guide to LaTeX*, 3rd ed. Harlow, England: Addison-Wesley, 1999.